Testing the Standard Model of Elementary Particle Physics II

7th lecture

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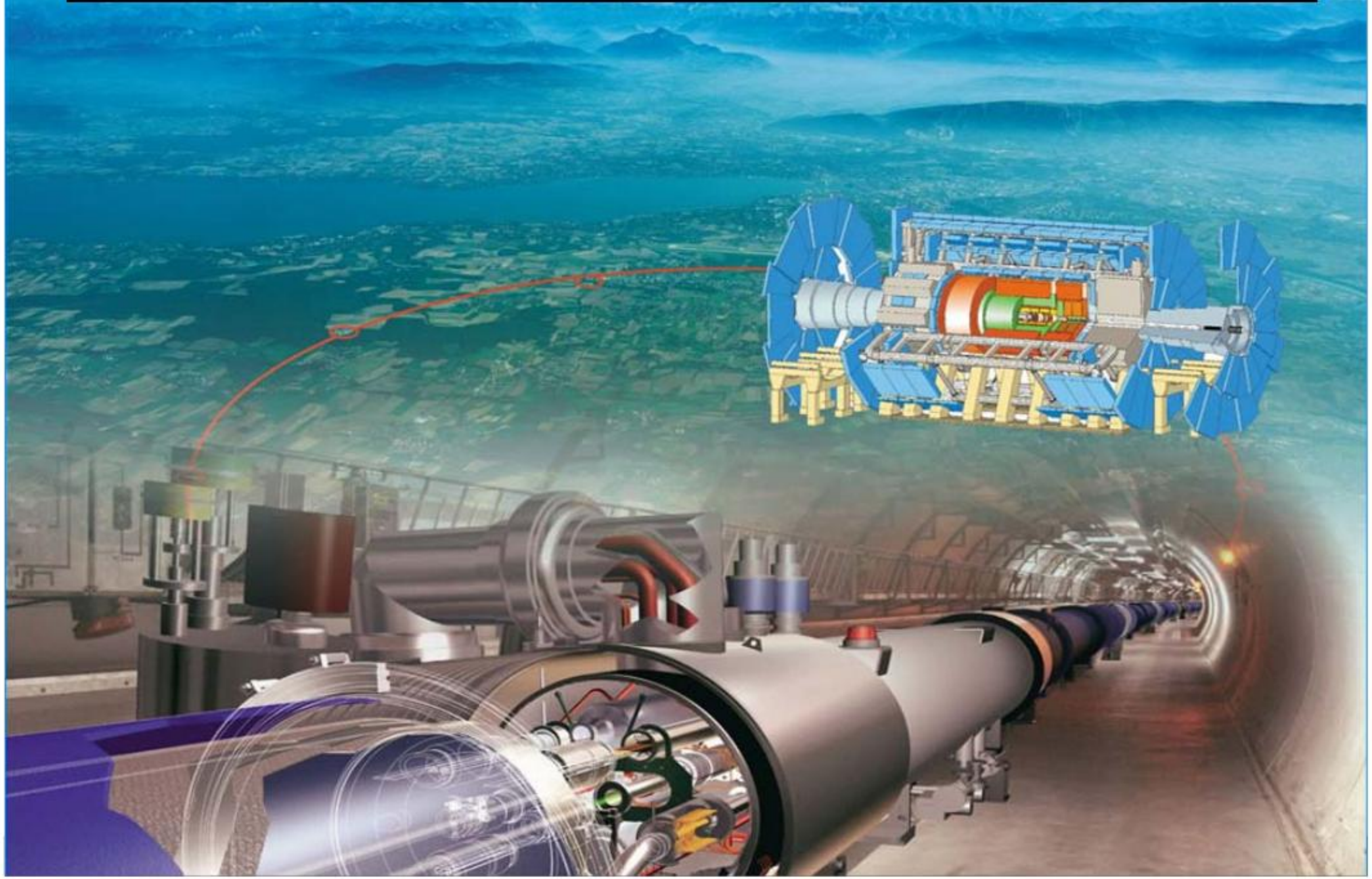
4.6 Neutrinos (Masses and Oscillation)



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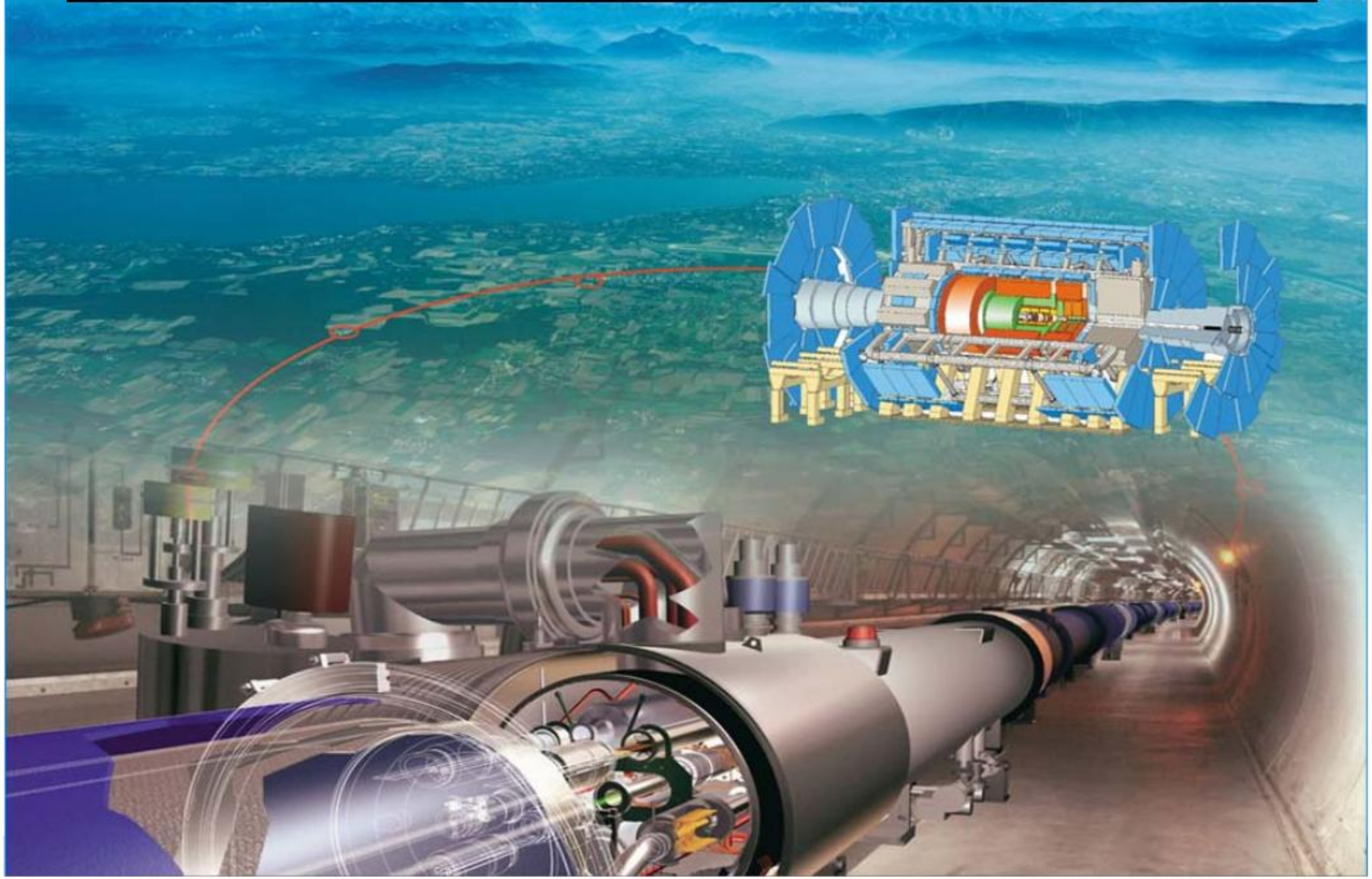
4.6.1 Neutrino Oscillation



Neutrino masses and oszillation

- **In the Standard Model, neutrinos are massless**
  - Only left-handed neutrinos (and right handed anti-neutrinos)
  - Right-handed neutrinos do not participate in the weak interaction

- **Neutrino oscillation:**
  - First observed in 1998
  - Implíes that neutrino must have nonzero mass
  - As well as violation of lepton flavour conservation, as for quarks

	Mass	Measurements	Discovery
ν_e	< 1.1 eV	KATRIN	Cowan. Reines 1956 (inverse β decay)
ν_μ	< 190 KeV	PSI Zürich	Ledermann. Schwartz, Steinberger 1962
ν_τ	< 18.2 MeV	ALEPH (LEP)	DONUT Experiment (FNAL) 2001

Neutrino masses and oszillation

- Massive neutrinos couple in the same way to the Higgs-field as quarks do:
  - The mass eigenstates of neutrinos differ from their flavour eigenstates
  - Mass matrix is not diagonal for the flavour eigenstates
  - Flavour and mass eigenstates are connected via a unitary transformation
- The unitary transformation for left-handed neutrino states:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = U_u \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

with the mass eigenstates ν_i (i = 1, ..., 3) and the flavour eigenstates ν_α (α = e, μ, τ):

$$\nu_i = \sum_\alpha U^*_{\alpha i}\, \nu_\alpha \; ; \quad \bar{\nu}_i = \sum_\alpha U_{\alpha i}\, \bar{\nu}_\alpha$$

$$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i \; ; \quad \bar{\nu}_\alpha = \sum_i U^*_{\alpha i}\, \bar{\nu}_i$$

Neutrino masses and oszillation

- As a consequence:
  - Time dependent oscillation between mixed states → **Neutrino oscillation**
- U_u is the **Pontecorvo-Maki-Nakagawa-Sakata** (PMNS) mixing matrix
  - If there are only n = 3 Majorana neutrinos, U_u is a 3 × 3 matrix analogous to the CKM matrix for the quarks
  - It depends on six independent parameters: three mixing angles and three phases

$$U_u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij} > 0$, $c_{ij} = \cos\theta_{ij} > 0$, a CP violating phase δ as well as the two Majorana phases Φ_1 and $\Phi_2 \in [0, 2\pi]$

More information can be found in: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Mass-Induced Flavour Oscillations in Vacuum

- After travelling a distance L, neutrino states evolve as:

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U_{\alpha i}^{*} \, |\nu_i(t)\rangle$$

- These neutrinos can then undergo a charged-current (CC) interaction producing a charge lepton ℓ_β, **$\nu_\alpha(t)$ N' $\rightarrow \ell_\beta$ N**, with a probability:

$$P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_{i=1}^{n}\sum_{j=1}^{n} U_{\alpha i}^{*} U_{\beta j} \langle\nu_j|\nu_i(t)\rangle\right|^2$$

- Assume that $|\nu_i>$ is a plane wave:

$$|\nu_i(t)\rangle = e^{-iE_i t}\,|\nu_i(0)\rangle$$

with: $E_i = \sqrt{p_i^2 + m_i^2} \approx p + \frac{m_i^2}{2p}$

More information can be found in: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Mass-Induced Flavour Oscillations in Vacuum

- Transition probability for neutrinos can be expressed as:

CP conserving

$$P_{\alpha\beta} = \underbrace{\langle \nu_i | \nu_j \rangle}_{\delta_{ij}} - 4 \sum_{i<j}^{n} \mathcal{R}e \left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \right] \cdot \sin^2 X_{ij}$$

$$+ \; 2 \sum_{i<j}^{n} \mathcal{I}m \left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \right] \cdot \sin 2X_{ij}$$

due to the orthogonality of the mass eigenstates

CP violating

$$X_{ij} = \frac{\left(m_i^2 - m_j^2 \right) L}{4E}$$

- Same derivation for antineutrino states would give a similar expression but with the exchange U → U*

- With the **oscillation lengths:** $L_{ij}^{osc.} = \dfrac{4\pi E}{|\Delta m_{ij}^2|}$

Mass-Induced Flavour Oscillations in Vacuum

For n = 2 generations

- Mixing between two neutrino generations (with mixing angle θ and oscillation frequency $\Delta m^2 = m^2_2 - m^2_1$):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Transition probability:

$$\boxed{P_{\alpha\beta} = \delta_{\alpha\beta} - (2\delta_{\alpha\beta} - 1)\sin^2 2\theta \sin^2 X}$$

Mass-Induced Flavour Oscillations in Vacuum

Characteristic values of L and E for experiments performed using various neutrino sources and the corresponding ranges of $|\Delta m^2|$ to which they can be most sensitive to flavour oscillations in vacuum. SBL stands for Short Baseline and LBL for Long Baseline.

Experiment		L (m)	E (MeV)	$\|\Delta m^2\|$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Propagation of Massive Neutrinos in Matter

- Neutrinos propagating in a dense medium can interact with the particles in the medium
- The probability of an incoherent inelastic scattering is very small
  - The characteristic cross section for v-proton scattering is of the order:

Fermi constant **square of the center of mass energy of the collision**

$$\sigma \sim \frac{G_F^2 s}{\pi} \sim 10^{-43}\ \mathrm{cm}^2 \left(\frac{E}{\mathrm{MeV}}\right)^2$$

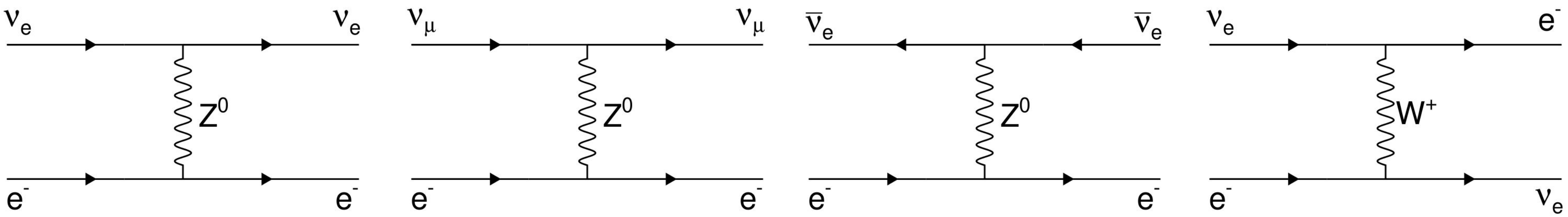
- When neutrinos propagate in dense matter, they can also interact coherently with the particles in the medium
  - In coherent interactions, the medium remains unchanged so it is possible to have **interference of the forward scattered and the unscattered neutrino waves** which enhances the oscillation effects

More information can be found in: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Propagation of Massive Neutrinos in Matter

- For neutrinos with relatively low energy (i.e. neutrinos from nuclear fusion in the sun), matter is transparent such that only elastic scattering with electrons give a significant cross section:
  - $E_v \leq 0.42$ MeV (pp-fusion)
  - $E_v \leq 14.6$ MeV (^{8}B-fusion)

- **Representative Feynman-diagrams:**



Propagation of Massive Neutrinos in Matter

For n = 2 generations

- **Oscillation probability**, taking varying potential (which depends on the density and composition of the matter) into account:

$$P_{\alpha\beta} = \left| \sum_i \tilde{U}_{\alpha i}(0)\tilde{U}_{\beta i}(L) \exp\left(-\frac{i}{2E}\int_0^L \mu_i^2(x^{'})dx^{'}\right)\right|^2$$

with the effective masses:

$$\mu_{1,2}^2(x) = \frac{m_1^2 + m_2^2}{2} + E[V_\alpha + V_\beta] \mp \frac{1}{2}\sqrt{[\Delta m^2 \cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2}$$

Potential

$$A = 2E(V_\alpha - V_\beta)$$

Resonance condition:

$$A_R = \Delta m^2 \cos 2\theta$$

Propagation of Massive Neutrinos in Matter

- **The Mihheev-Smirnov-Wolfenstein Effect for Solar Neutrinos:**
  - Matter effects are relevant for solar neutrinos
    - In particular if the sun produces ν_e in its core (have to consider the propagation of a ν_e − ν_X neutrino system, with X indicating superposition of μ and τ)
  - The density of solar matter decreases monotonically as a function of the distance R from the center of the sun (for $R < 0.9\, R_\odot$):

$$n_e(R) = n_e(0) e^{-10.5 R/R_\odot}$$

  - Distinguish between **three relevant cases**
    - After crossing the sun, the composition of the neutrino state exiting the sun will depend on the relative size of $\Delta m^2 \cos 2\theta$ versus $A_0 = 2\, E\, G_F\, n_{e,0}$ (with $n_{e,0}$ being the density at the point of neutrino production)

Propagation of Massive Neutrinos in Matter

1) If the relevant matter potential at the production point is well below the resonant value, $A_R = \Delta m^2 \cos 2\theta >> A_0$, matter effects are negligible (propagation occurs as in vacuum):

$$P_{ee}\left(\Delta m^2 \cos 2\theta >> A_0\right) = 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$$

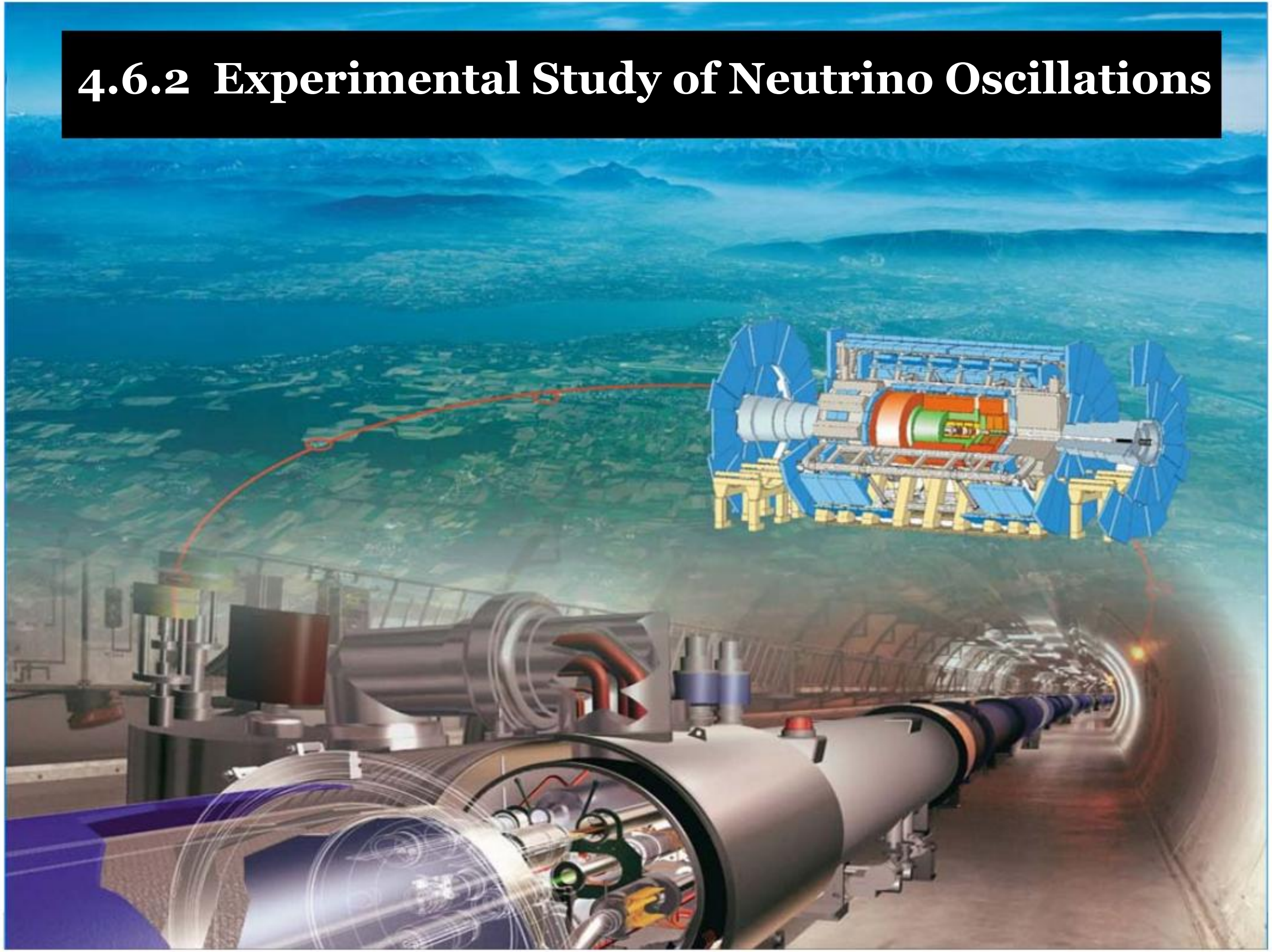
2) If the relevant matter potential at production is only slightly below the resonant value, $A_R = \Delta m^2 \cos 2\theta \sim A_0$, the neutrino does not cross a region with resonant density, but matter effects are sizable enough to modify the mixing:

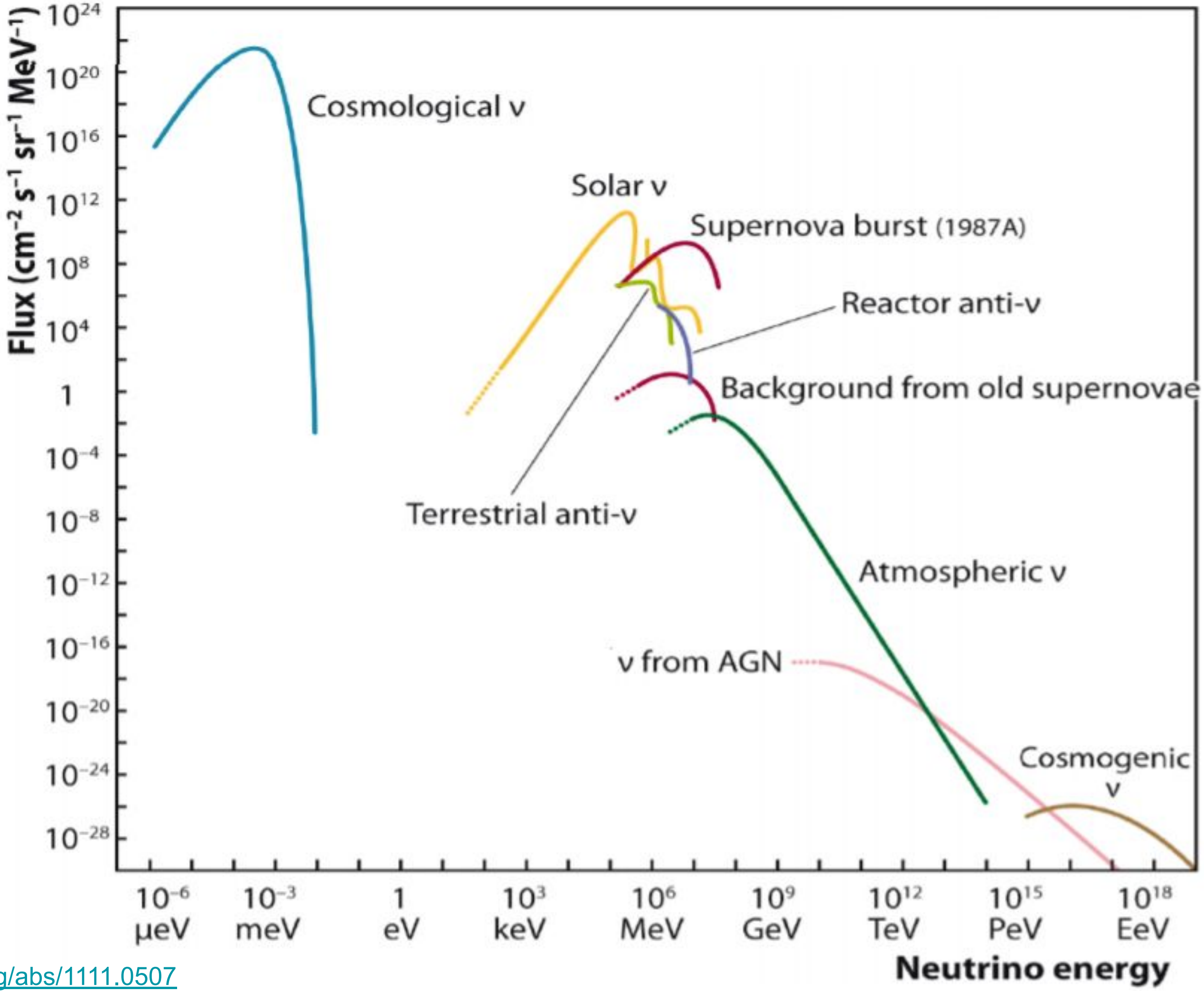
$$P_{ee}\left(\Delta m^2 \cos 2\theta \geq A_0\right) = \cos^2\theta_{m,0}\cos^2\theta + \sin^2\theta_{m,0}\sin^2\theta = \frac{1}{2}\left[1 + \cos 2\theta_{m,0}\cos 2\theta\right]$$

3) In the case that $A_R = \Delta m^2 \cos 2\theta < A_0$, the neutrino can cross the resonance on its way out:

$$P_{ee}\left(\Delta m^2 \cos 2\theta < A_0\right) = \frac{1}{2}\left[1 + \cos 2\theta_{m,0}\cos 2\theta\right] = \sin^2\theta$$

4.6.2 Experimental Study of Neutrino Oscillations





Taken from: https://arxiv.org/abs/1111.0507

Atmospheric neutrinos

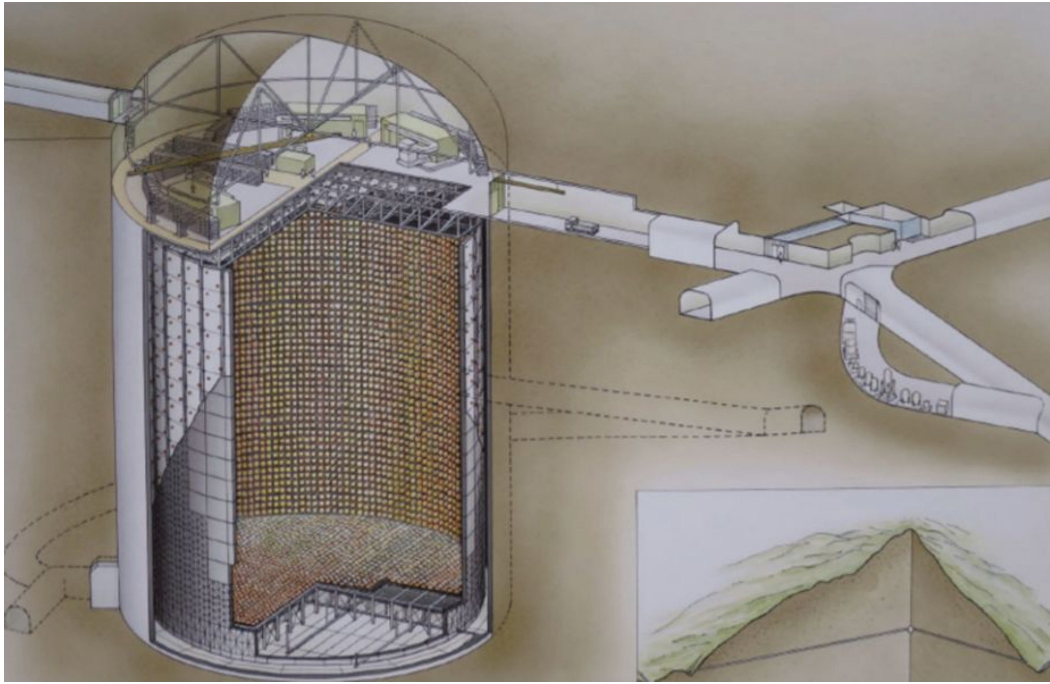
- **Atmospheric neutrino flux**
  - The primary cosmic rays, mostly protons, interact with molecules of the atmosphere and produce pions and kaons.
    - Neutrinos are created by the decay of $\pi/K \rightarrow \mu + \nu_\mu$ and also by the subsequent decay of $\mu \rightarrow e + \nu_\mu + \nu_e$
    - They have a broad range of energy (~0.1 GeV to >TeV) and long travel distances before detection (~10 to 1.3×10^4 km)

- **Experiments:**
  - **Early experiments:**
    - Kamiokande or IMB (based on water Cherenkov detectors)
    - Frejus or NUSEX (based on iron tracking calorimeters)
  - **Recent experiments:**
    - Super-Kamiokande
    - OPERA
    - ANTARES and IceCube (although they mainly target high energy neutrinos)

Detection of Atmospheric Neutrinos

- How to detect atmospheric neutrinos (with Super-Kamiokande):
  - $\nu + N \rightarrow l + N'$ $(+ \pi/K)$

Taken from: https://link.springer.com/content/pdf/10.1140/epjc/s10052-019-6796-2.pdf

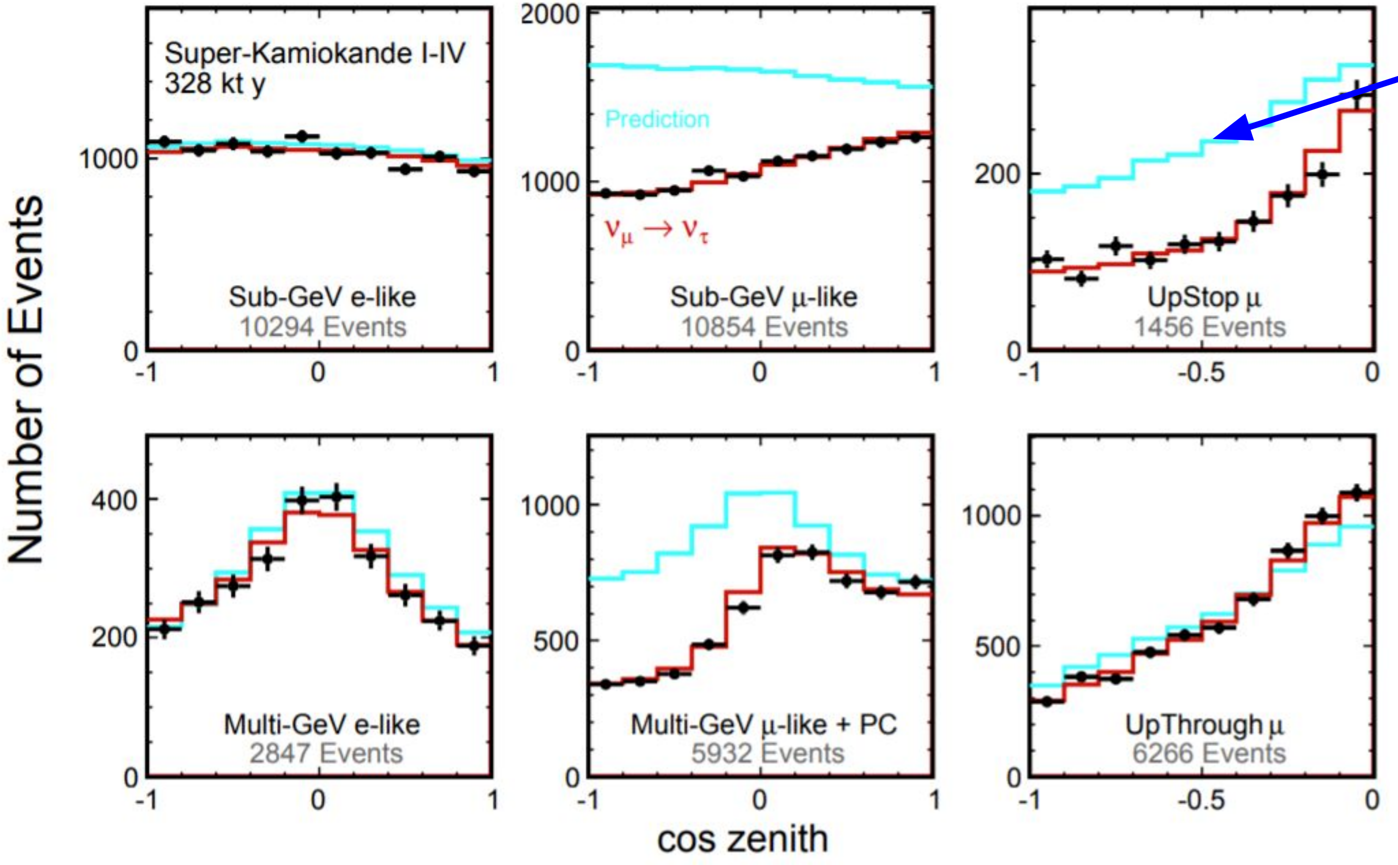


- **Super-Kamiokande Detector**:
  - The 50 kton water
  - 11000 photomultiplier tubes
  - Placed 1000m underground

- Events in Super-K are classified into different event types:
  - Upward going muons (Up-μ):
  - Upward stopping muons (Stop-μ)
  - Others ...

Super-Kamiokande

Atmospheric neutrinos



Predictions (in absence of oscillations)

The zenith angle distributions of Super-Kamiokande atmospheric neutrino events.

Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

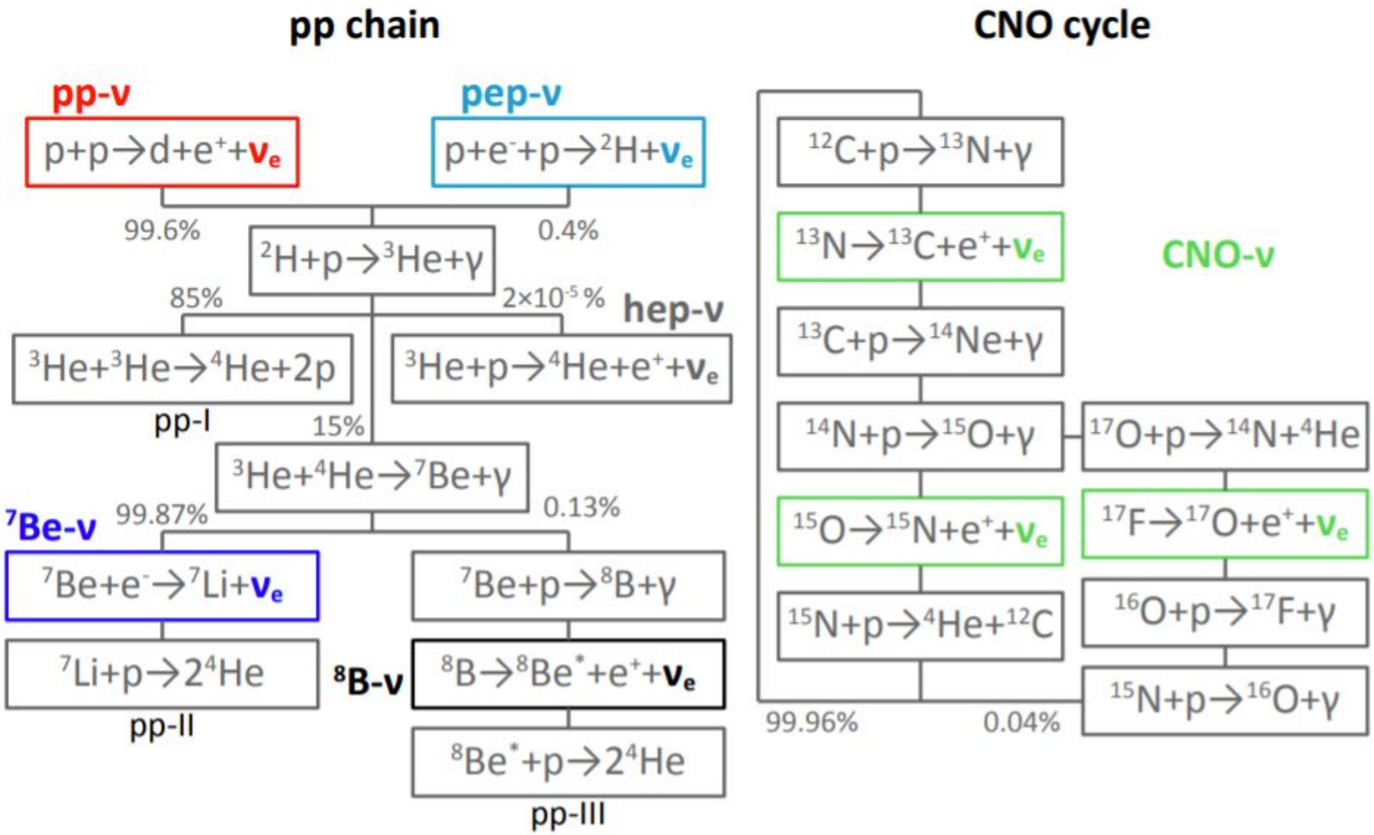
Solar neutrinos

- In the Sun, electron neutrinos are produced in the thermonuclear reactions which generate the solar energy
  - These reactions occur via two main processes, the **pp chain** and the **CNO cycle**
  - Result in the overall fusion of protons into:

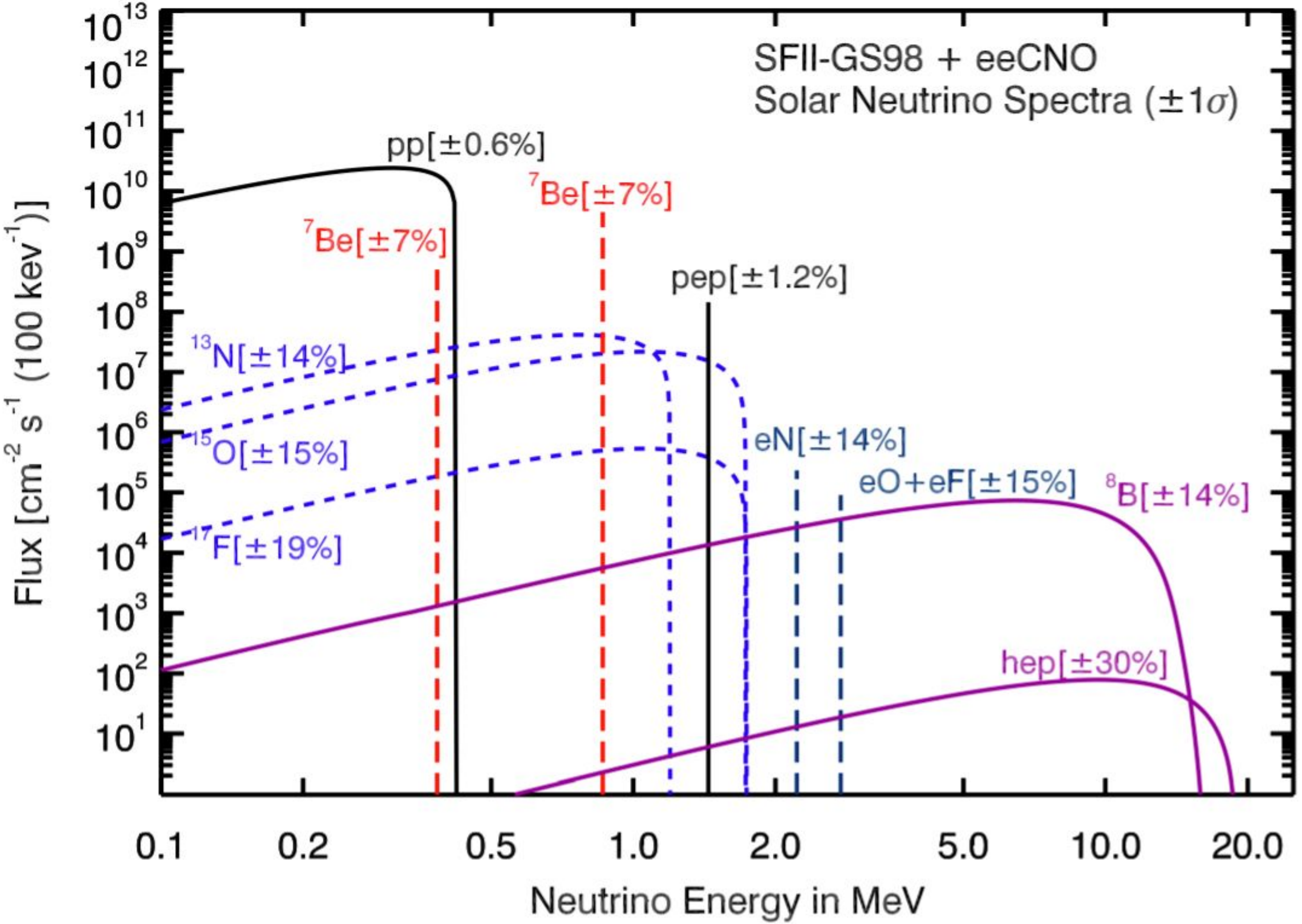
$$\boxed{4p \rightarrow He^4 + 2e^+ + 2\nu_e + 26.73\ \text{MeV}}$$

  where most of the energy is radiated through photons and only a small fraction is carried by neutrinos **$\langle E_{2\nu} \rangle$ = 0.59 MeV**
  - In addition, electron capture on ^{13}N, ^{15}O, and ^{17}F produces line spectra of neutrinos called ecCNO neutrinos
  - At the Earth, the pp solar neutrino flux is determined to be $6 \times 10^{10}\ cm^{-2}s^{-1}$
    - Based on the Standard Solar Model (SSM)

Solar neutrinos



Taken from: https://iopscience.iop.org/article/10.1088/1742-6596/1056/1/012050f



SFII-GS98 + eeCNO
Solar Neutrino Spectra (±1σ)
pp[±0.6%]
7Be[±7%]
7Be[±7%]
pep[±1.2%]
13N[±14%]
15O[±15%]
17F[±19%]
eN[±14%]
eO+eF[±15%]
8B[±14%]
hep[±30%]
Flux [cm-2 s-1 (100 kev-1)]
Neutrino Energy in MeV
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1

Solar neutrino experiments

List of former and ongoing solar neutrino experiments

Name	Target material	Energy threshold (MeV)	Mass (ton)	Years
Homestake	C_2Cl_4	0.814	615	1970–1994
SAGE	Ga	0.233	50	1989–
GALLEX	$GaCl_3$	0.233	100 [30.3 for Ga]	1991–1997
GNO	$GaCl_3$	0.233	100 [30.3 for Ga]	1998–2003
Kamiokande	H_2O	6.5	3,000	1987–1995
Super-Kamiokande	H_2O	3.5	50,000	1996–
SNO	D_2O	3.5	1,000	1999–2006
KamLAND	Liquid scintillator	0.5/5.5	1,000	2001–2007
Borexino	Liquid scintillator	0.19	300	2007–

Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Detection of solar neutrinos and the solar neutrino problem

- Early solar neutrino experiments (e.g. Homestake):

Based on: $\boxed{\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}}$

  - Most relevant fluxes are from the ^{7}Be and ^{8}B neutrinos (because the process energy threshold of 814 keV)
  - The detector contained ~ 615 t of C_2Cl_4
  - The produced ^{37}Ar, which has a half life of 34.8d, was chemically extracted and introduced into a low-background proportional chamber every few months.
    - The Auger electrons from electron capture of ^{37}Ar were counted to determine the reaction rate.
  - Of course the observed number of neutrinos in the Homestake mine experiment was significantly smaller than the prediction by SSM

→ **solar neutrino problem**

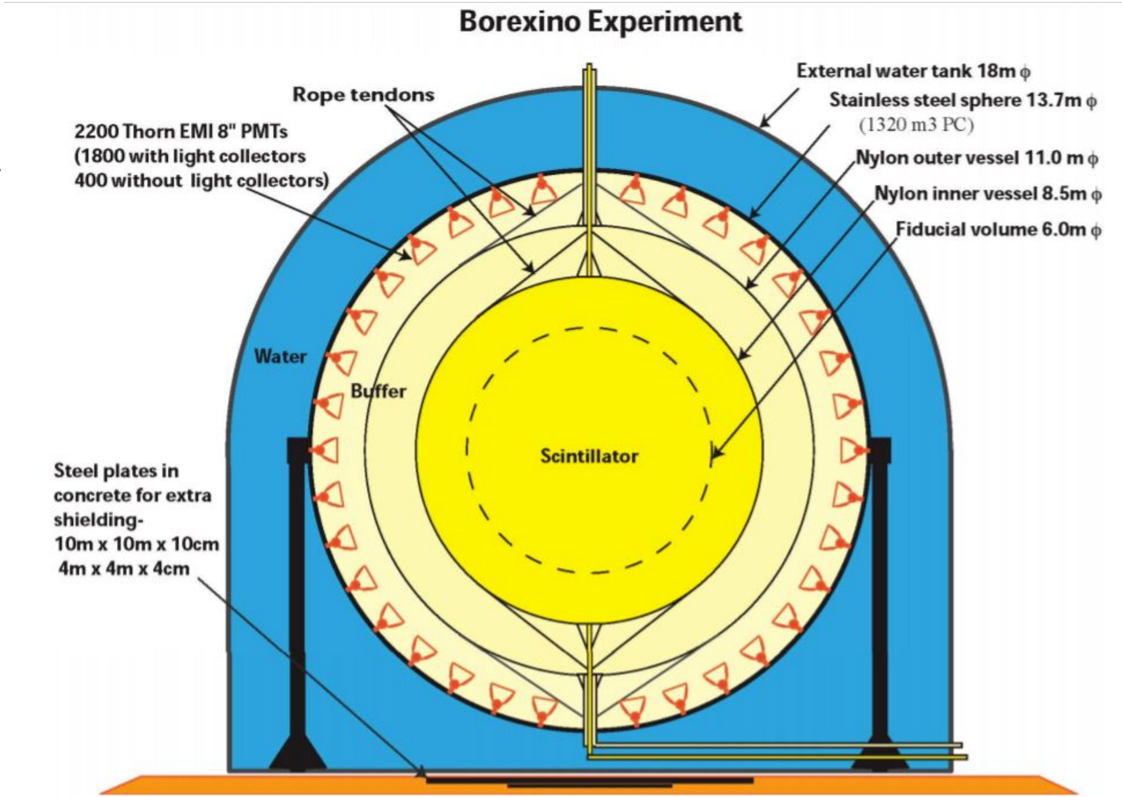
Further information: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Solar neutrinos

- **Borexino is a liquid scintillator**
  - Primary goal: Measure the fluxes of solar neutrinos
  - Located in the Laboratori Nazionali del Gran Sasso at a depth of 3800m water-equivalent

  - Detection of neutrinos via elastic scattering with electrons of the organic scintillator molekules

$$\nu\, e^- \rightarrow \nu\, e^-$$



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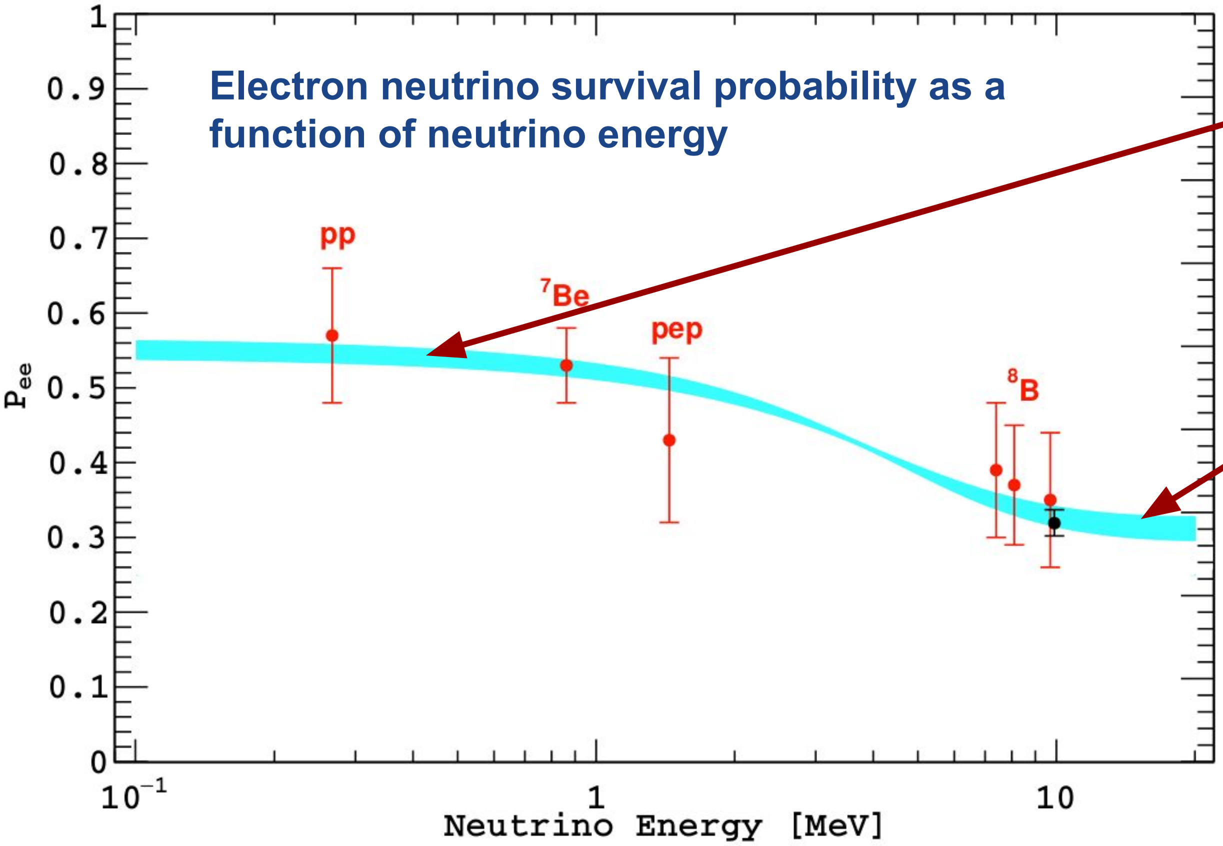
Solar neutrinos

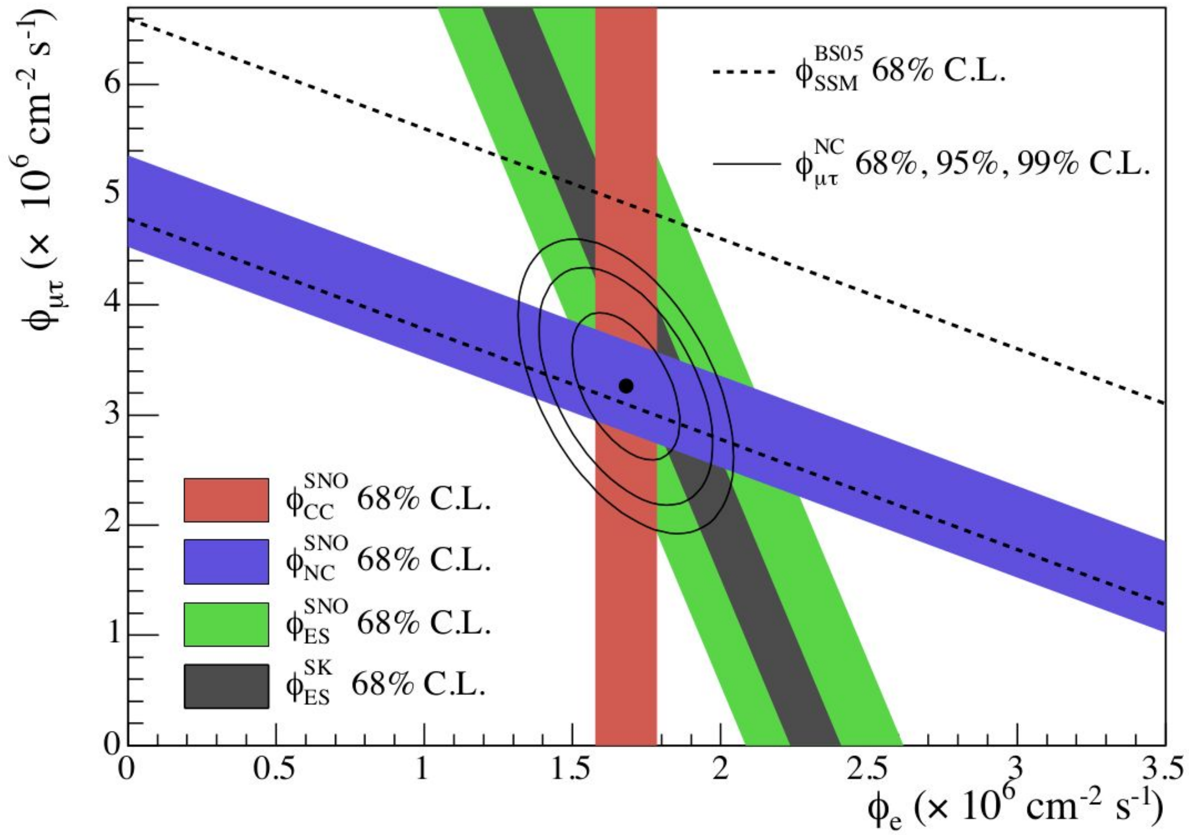


$\Delta m^2 \cos 2\theta \gg A_0$

$\Delta m^2 \cos 2\theta \ll A_0$

Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Solar neutrinos



Fluxes of ^{8}B solar neutrinos, $\varphi(\nu_e)$, and $\varphi(\nu_{\mu,\tau})$, deduced from results provided by SNO and Super-Kamiokande

Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

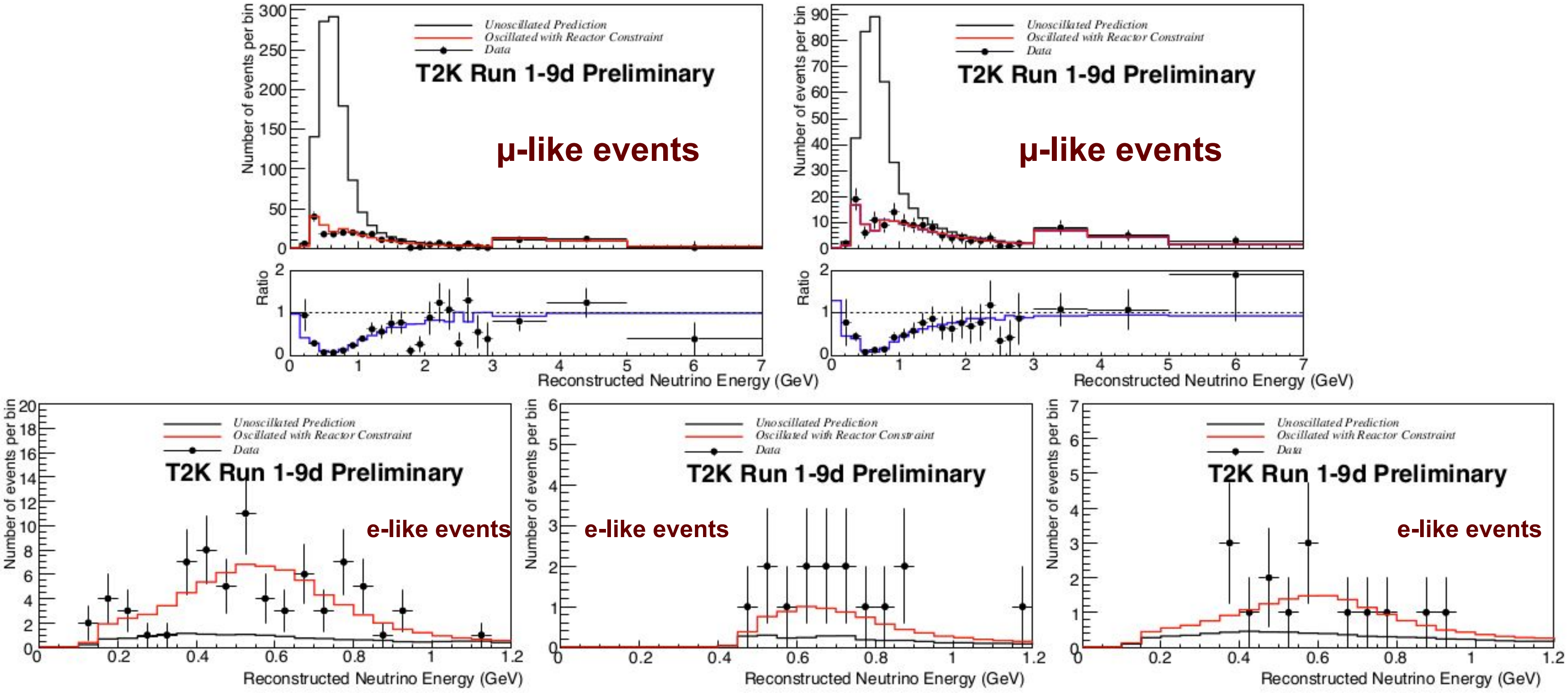
Accelerator Neutrinos

- Conventional neutrino beams from accelerators are produced by colliding high energy protons onto a target.
  - **Producing π and K which then decay into neutrinos**
    - Other particles are stopped via a beam dump
  - Magnets are used to concentrate the neutrino beam flux towards the desired direction
  - Neutrino energy is proportional to pion energy

Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–

Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Accelerator Neutrinos



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Reactor Neutrino Experiments

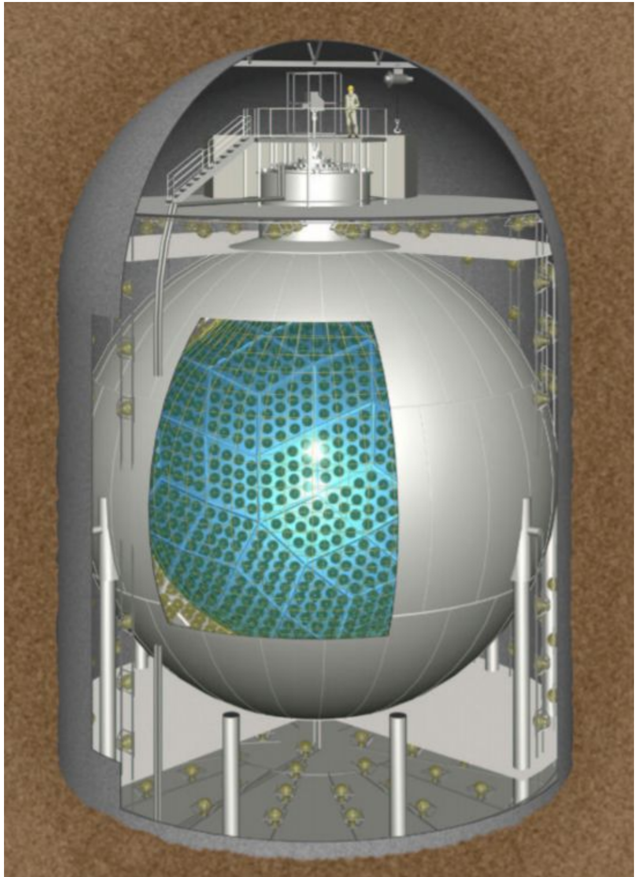
- Nuclear reactors are very intense sources of anti-electron neutrinos in the MeV energy region, which are generated in nuclear fission of heavy isotopes (mainly ^{235}U, ^{238}U, ^{239}Pu, or ^{241}Pu)
  - The neutrino flux from a reactor can be estimated based on the thermal power output and fuel composition as a function of time

Name	Reactor power (GW_{th})	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	

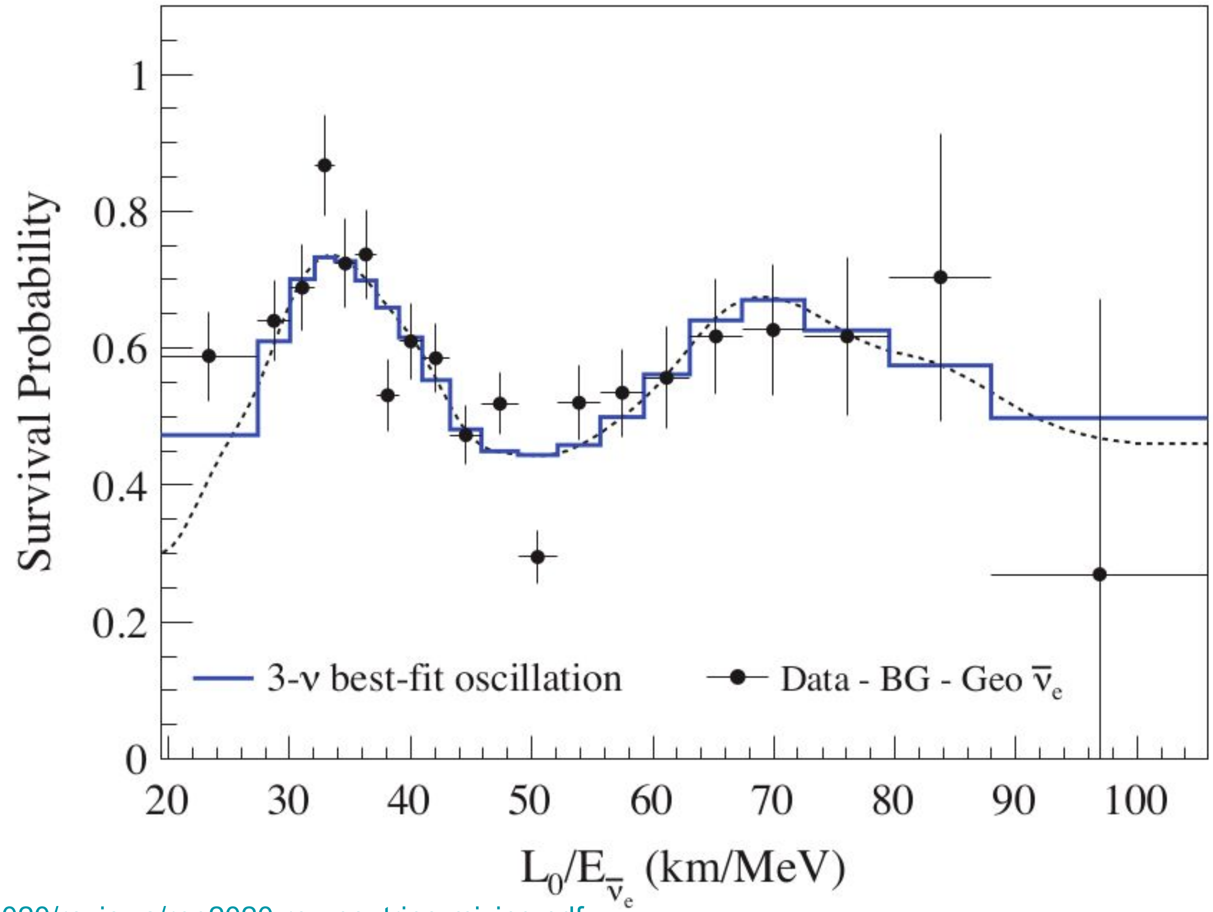
Taken from: https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

Reactor Neutrinos

- **KamLAND** (*Kamioka Liquid Scintillator Antineutrino Detector*)
  - Uses 1,000 t of ultra-pure liquid scintillator contained in a 13m diameter spherical balloon
  - Located in the original Kamiokande cavern, where the neutrino flux is dominated by a few reactors at an average distance of ~180 km
  - Reported first results in 2002 show that the **ratio of the observed number of anti-electron neutrinos and the expectations is: 0.611 ± 0.085 ± 0.041**



Reactor Neutrinos



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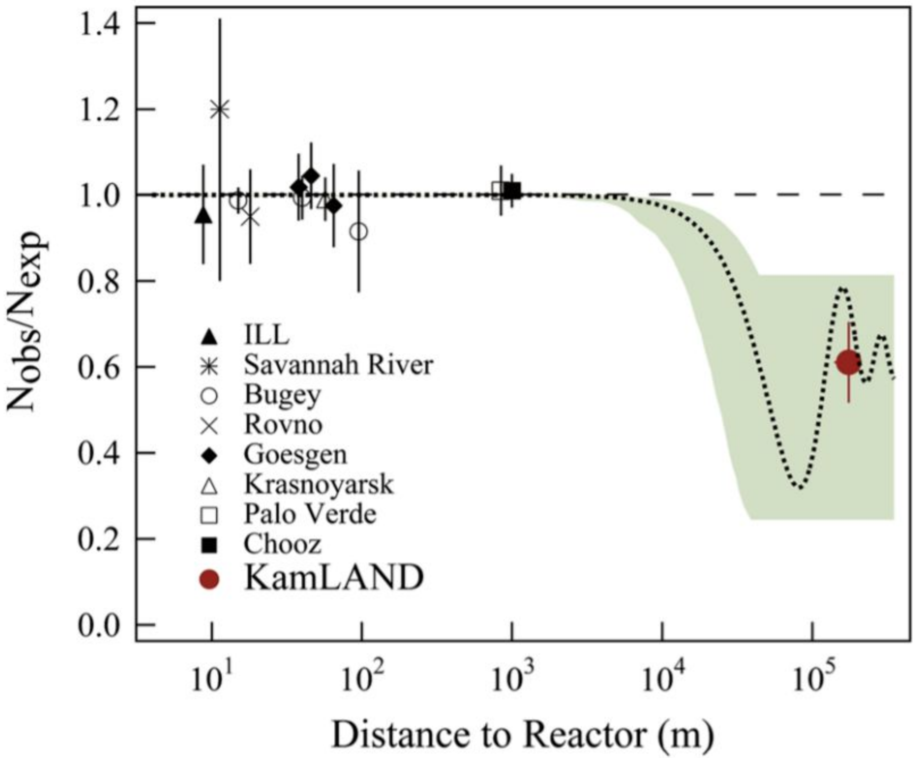
Reactor Neutrinos

- The ratio of measured to expected ν_e flux from reactor experiments



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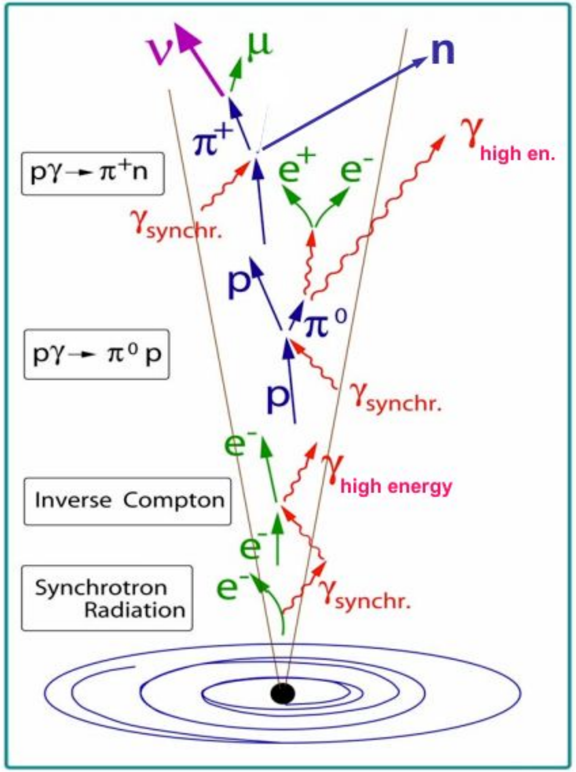
Neutrinos from cosmic accelerators

- **Neutrinos from cosmic accelerators:**
  - Galactic sources:
    - **Supernova remnants (SNR)**
  - Extragalactic sources:
    - **Active Galactic Nuclei** (i.e. supermassive black holes with 10^6 –10^9 solar masses that accrete matter and thus transform huge amounts of gravitational energy into radiation)
    - **Gamma Ray Bursts** (i.e. events releasing huge amounts of energy in gamma rays with milliseconds to minutes. The favoured explanation for the longer bursts is the collapse of a massive star into a black hole)
    - **Starburst galaxies** (i.e. galaxies undergoing an episode of large-scale star formation, where the central regions eject a galactic-scale wind driven by the collective effect such as supernova explosions)



Taken from: https://arxiv.org/abs/1111.0507

Neutrinos from cosmic accelerators

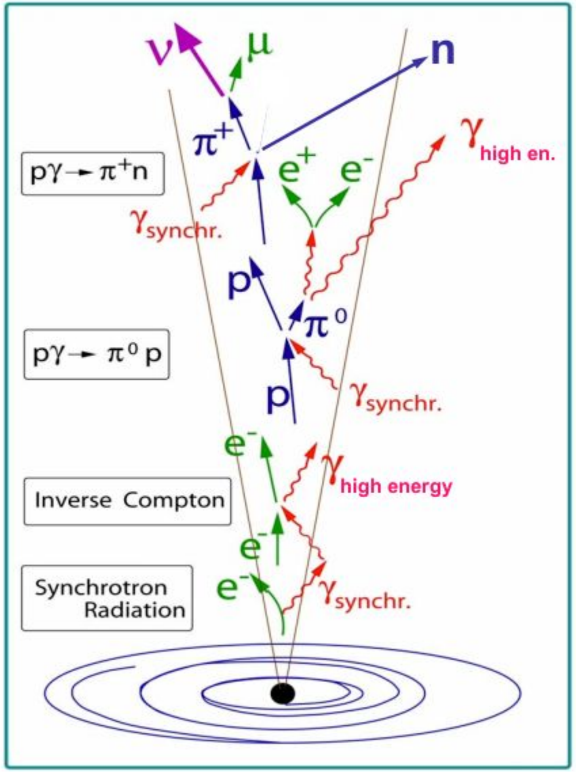
- **Neutrinos from cosmic accelerators:**
  - Neutrino production:
    - Protons from cosmic accelerators generate neutrinos, via charged pion production due to collisions with matter or radiation fields:

$$p + \text{nucleus} \to \pi + X \; (\pi = \pi^{\pm}, \pi^0)$$

$$p + \gamma \to \Delta^+ \to \pi^0 + p$$

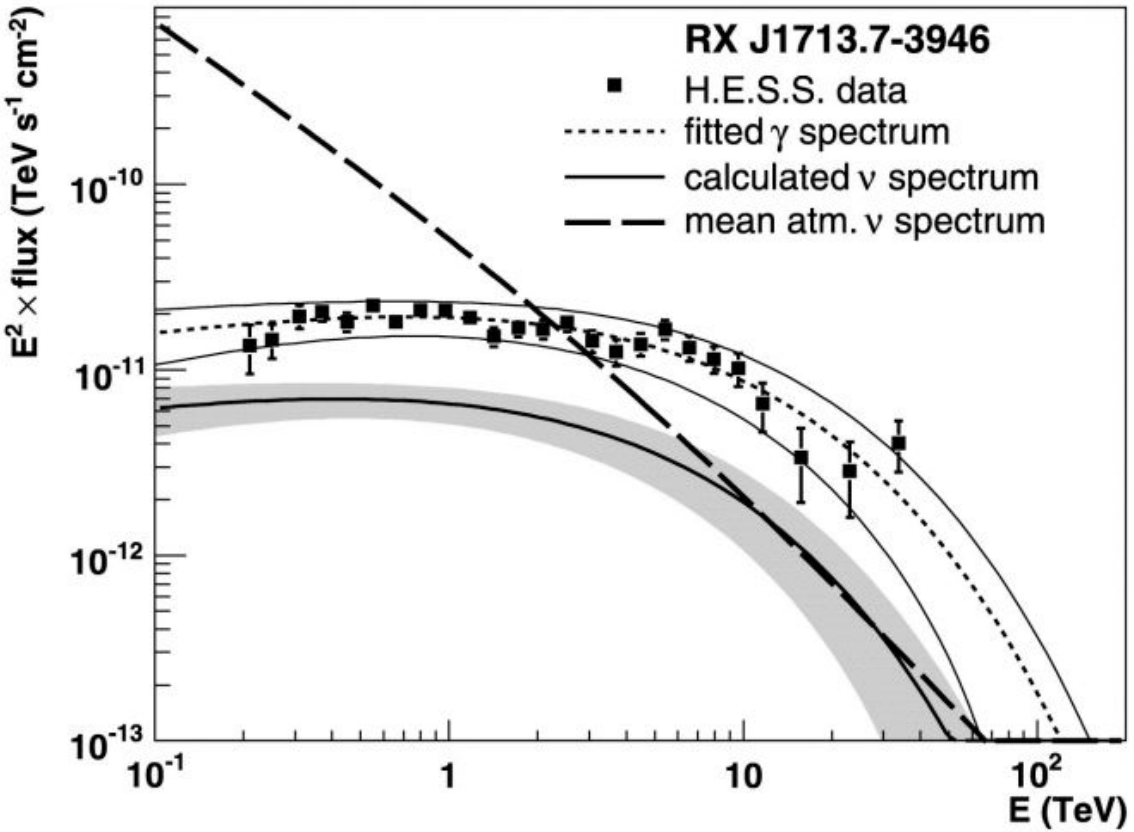
$$\pi^0 \to \gamma\gamma, \quad \pi^+ \to \mu^+ \nu_\nu, \quad \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

    - The neutrino flavour ratio:
      - **At the source:** $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$
      - **At earth:** $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$



Taken from: https://arxiv.org/abs/1111.0507

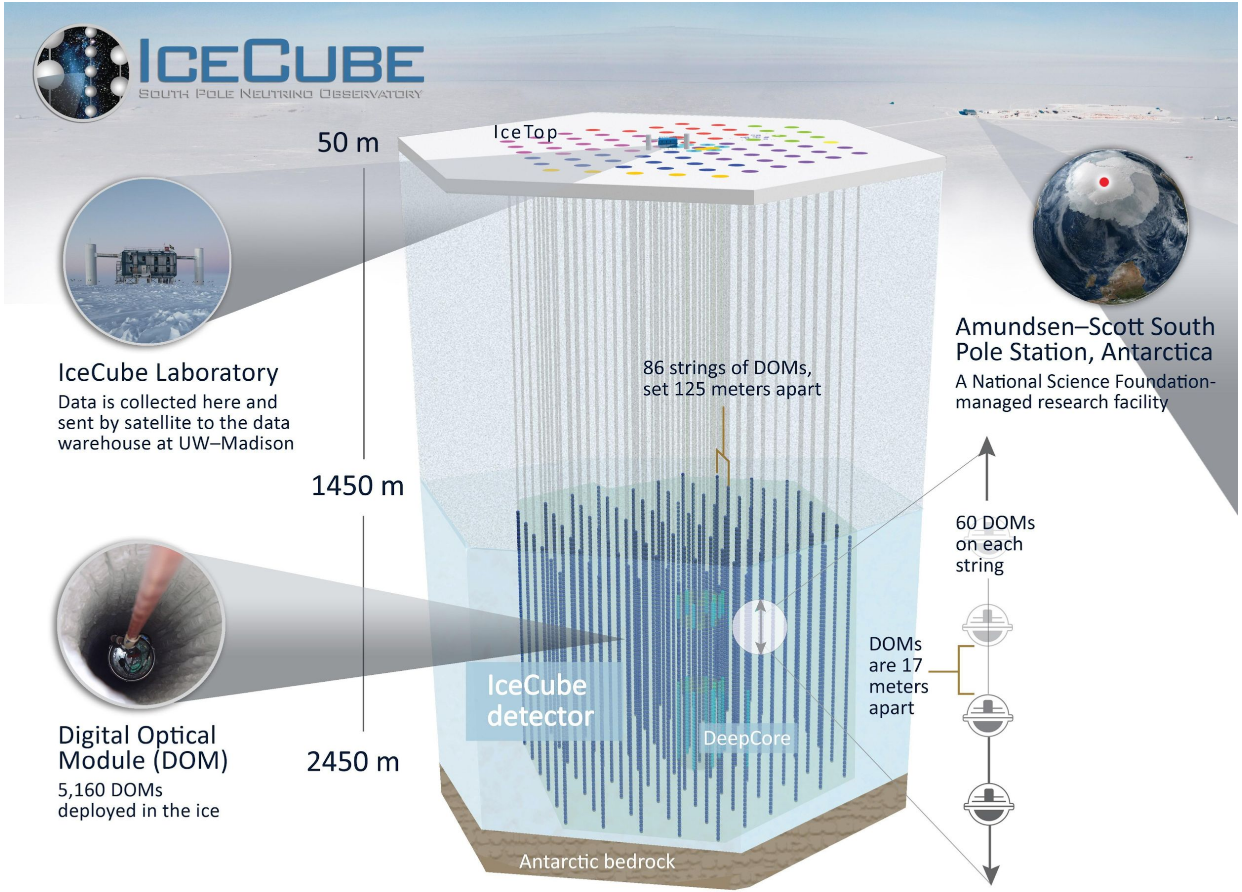
Neutrinos from cosmic accelerators



Expected neutrino flux from the SNR RX J1713.7-3946

Taken from: https://arxiv.org/abs/1111.0507

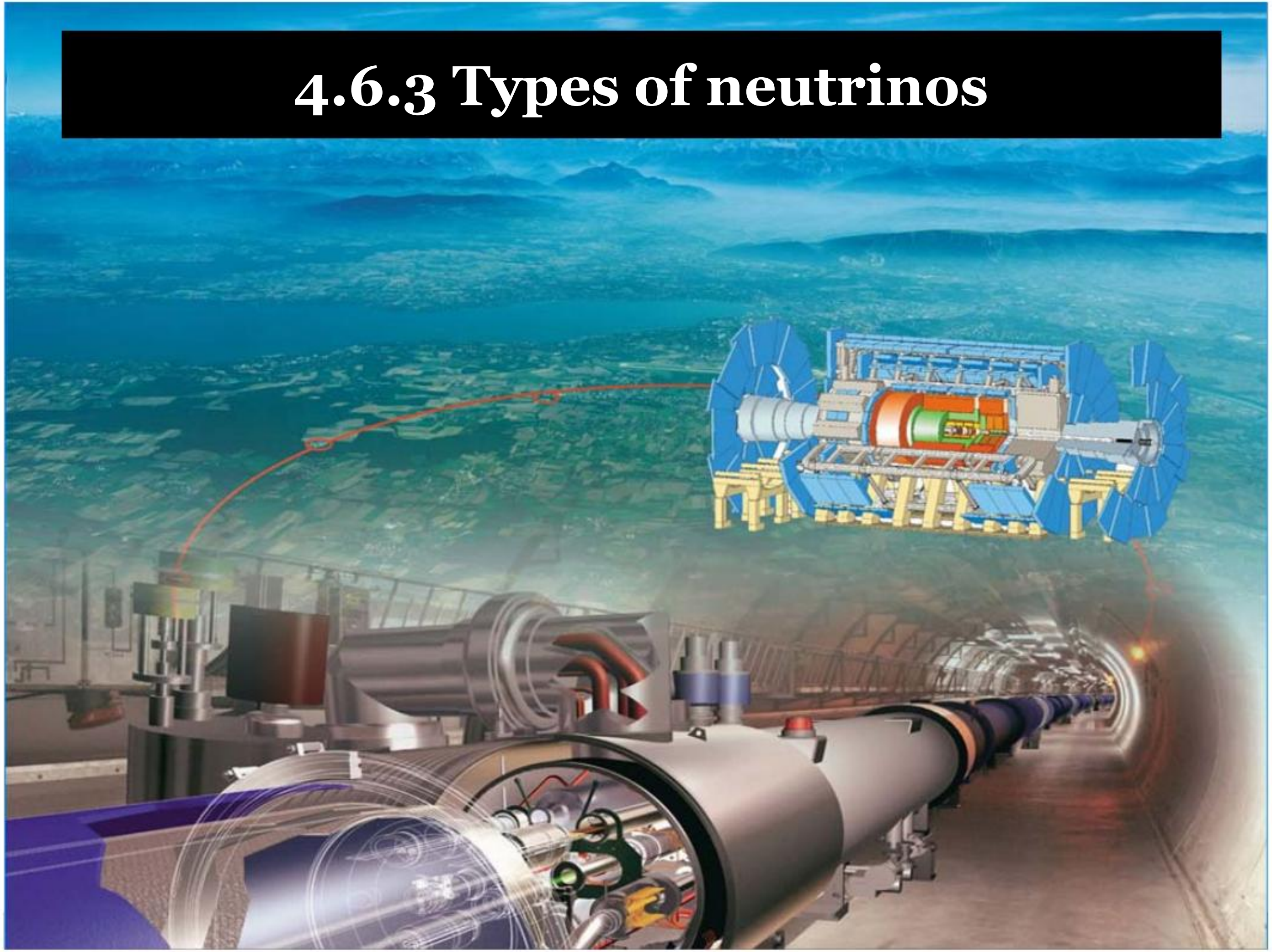
The IceCube Detector



ANTARES

ANTARES consists of a sparse array of PMTs deployed under the Mediterranean Sea at a depth of about 2.5 km to instrument a $10^5 m^3$ volume

4.6.3 Types of neutrinos



Types of Neutrinos

- **Dirac-Neutrinos:**
  - Neutrino and antineutrino are different
- **Majorana-Neutrino:**
  - Neutrinos with definite masses are Majorana particles
  - Majorana mass term → See-saw mechanism
    - Would explain why neutrino masses are so much smaller than masses of other SM particles
    - See-saw mechanism for neutrino masses are described in e.g. SO(10) Grand Unified Theories
      - Require heavy neutrinos beyond the scale of electroweak symmetry breaking
        - Dark matter candidates
- **Sterile Neutrinos:**
  - Hypothetical particles which are assumed to interact only via gravity and not via any other the fundamental interactions of the SM

Neutrinoless double beta decay

- Neutrinoless double beta decays (0νββ) are the most sensitive probes to whether neutrinos are Dirac or Majorana states
  - In order to induce the 0νββ decay, neutrinos must be Majorana particles
  - The 0νββ decay leads to a lepton number violation

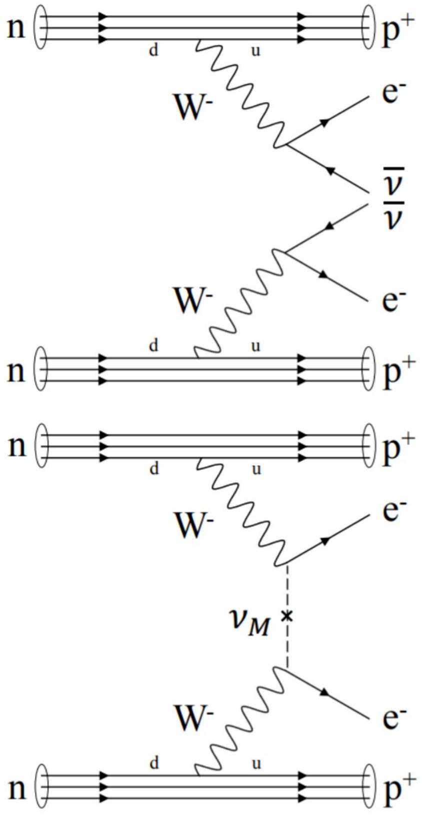
- The half-life of the decay is to be determined by experiments (assuming that the Majorana neutrino mass is the only source of lepton number violation at low energies):

nuclear matrix element of the transition

effective Majorana mass of ν_e

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{m_{ee}}{m_e}\right)^2$$

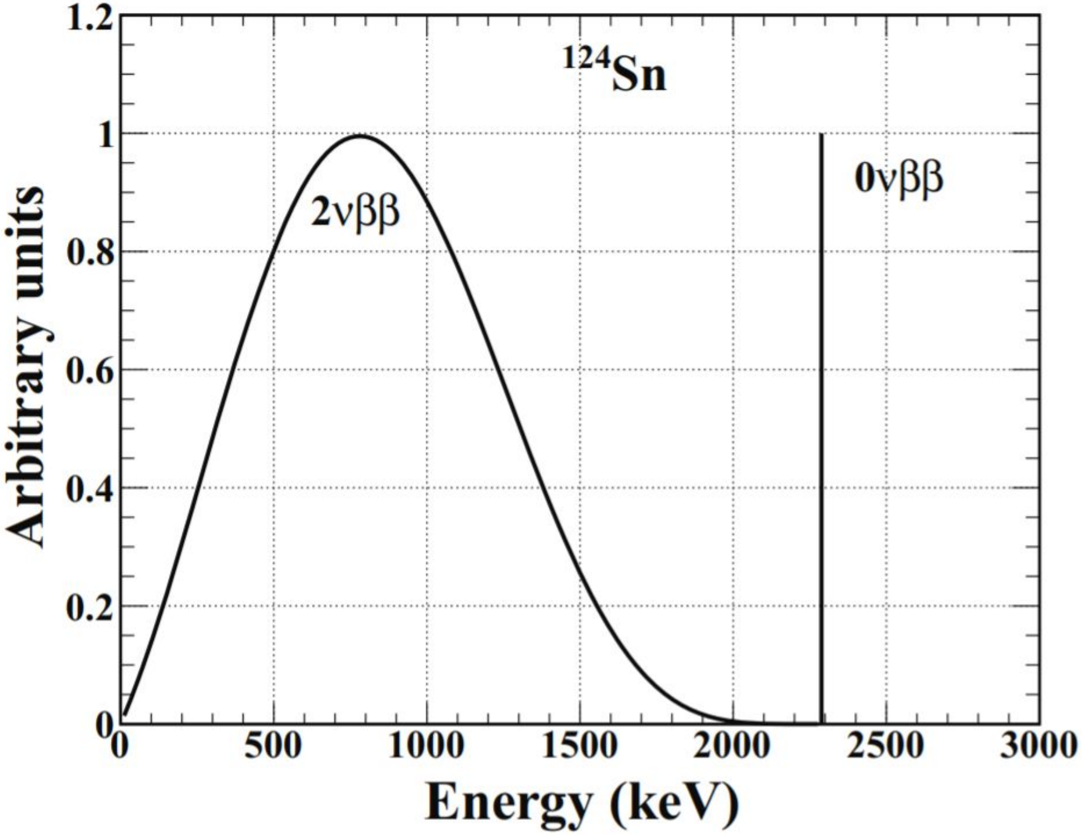
phase space integral taking into account the final atomic state



Neutrinoless double beta decay

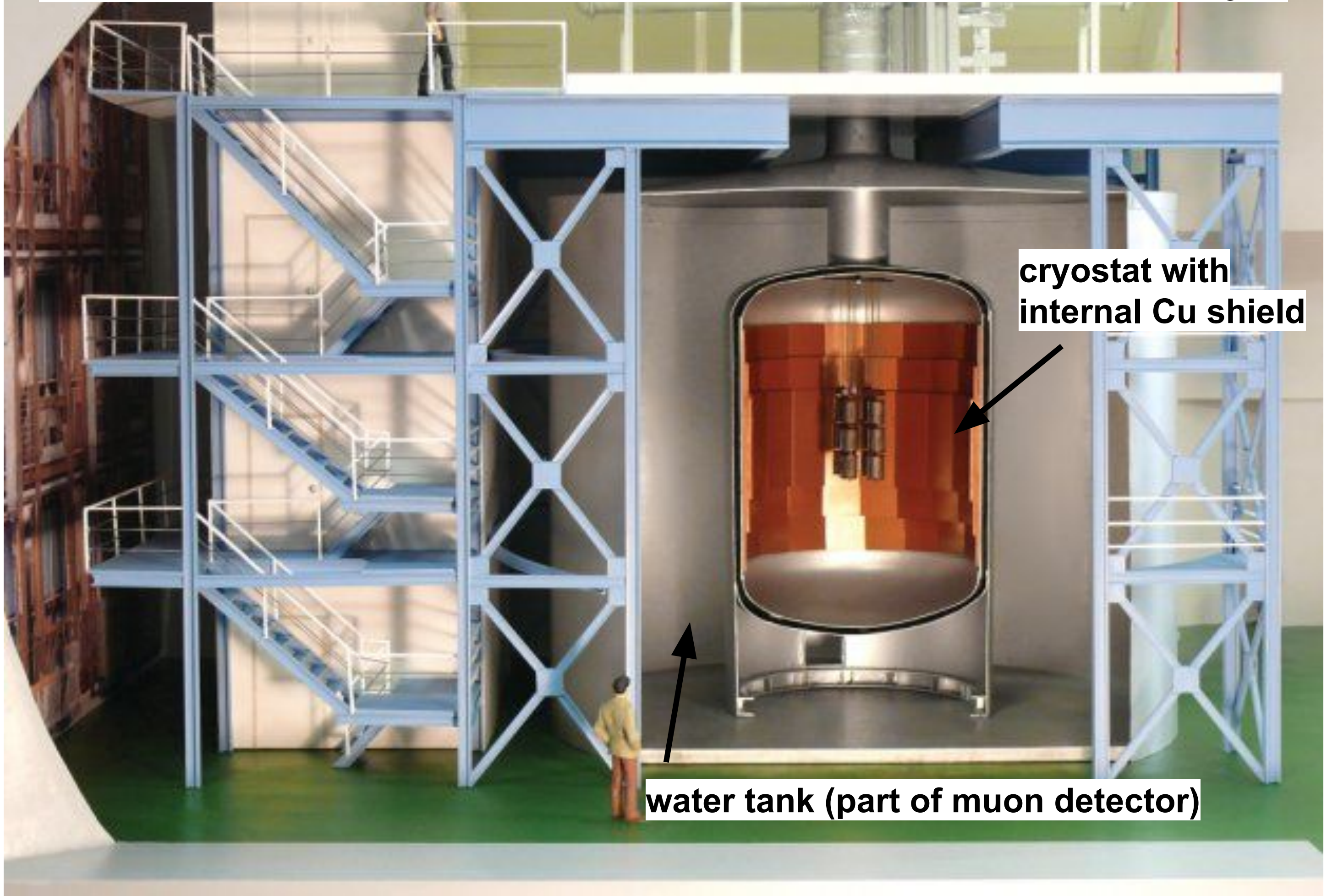
- Experimental Search for Neutrinoless Double-beta Decay:
  - The $0\nu\beta\beta$ signature: sum of energy of two electrons is equal to the Q-value of the nuclear transition.
  - The sensitivity to the half-life is proportional to:
    - Detection efficiency of the signal
    - Source mass
    - The background rate
    - The energy resolution
  - There are 35 candidate nuclei for double-beta decay
    - Recent experiments use: ^{76}Ge or ^{136}Xe
  - The energy from the outgoing electrons is measured with either ionization or scintillation
  - Recent Experiments:
    - **GERDA**
    - **AMoRE**
    - **NEMO-3**
    - **COBRA** (more information can be found here)

Neutrinoless double beta decay

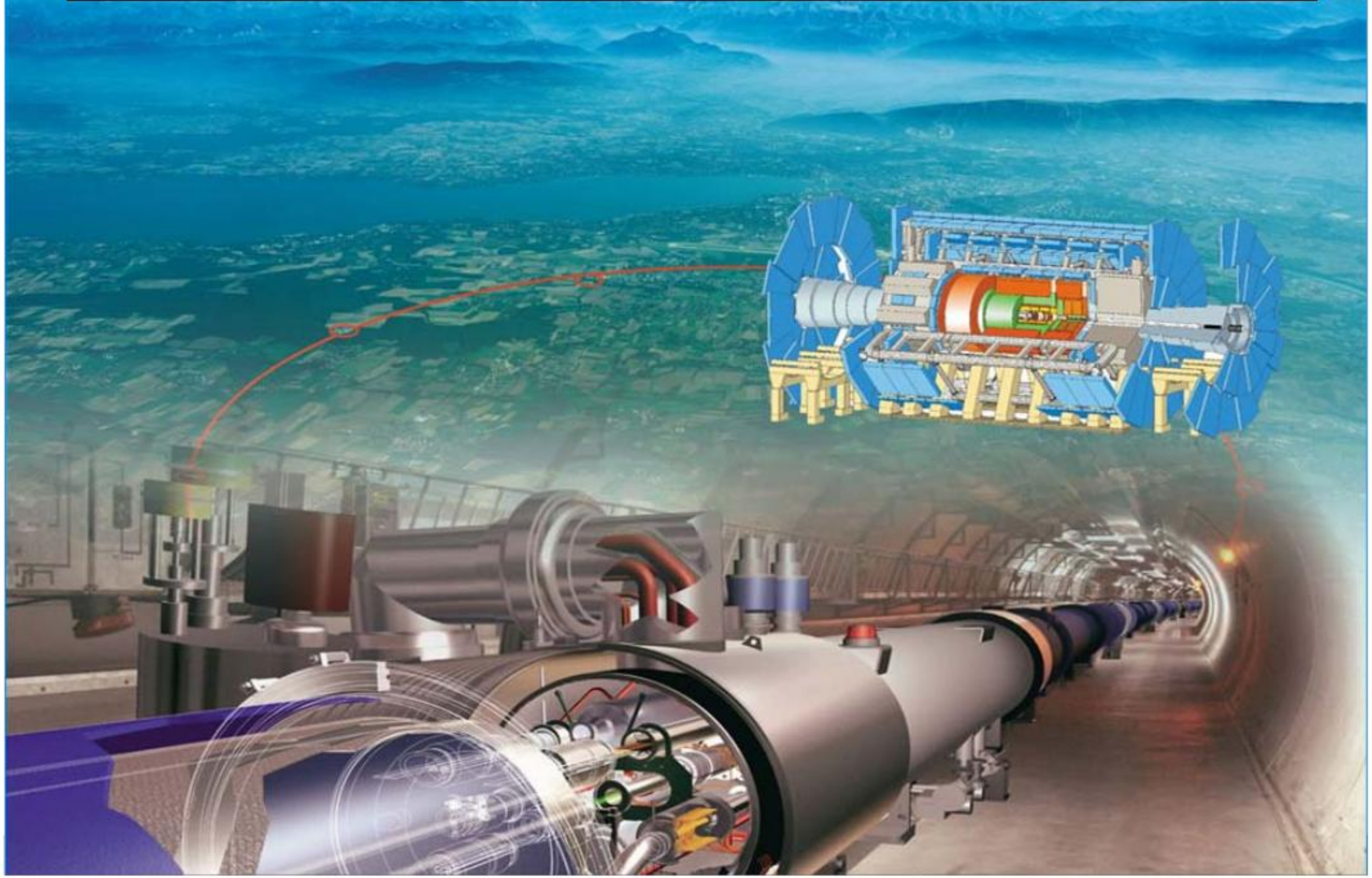


Taken from: https://link.springer.com/content/pdf/10.1007/s12648-019-01569-6.pdf

GERDA (GERmanium Detector Array)



4.6.4 Neutrino mass measurements



Neutrino mass measurements

- Limits on masses of ν_μ and ν_τ are set based on studies of:
  - Pion decays into muons and ν_μ (at PSI)
  - Investigation of τ -decays into 5 pions and ν_τ (at LEP)
- Upper limits:
  - **$m(\nu_\mu) < 190$ keV at 90 % CL**
  - **$m(\nu_\tau) < 18.2$ MeV at 95 % CL**
- Both limits are much larger than the interesting range of neutrino mass values
- However, experiments investigating the mass of the electron neutrino ν_e by analysing β decays with emission of electrons are providing a sensitivity in the interesting energy range (< eV)

Neutrino mass measurements

- **Tritium β decay:**
  - The most sensitive direct studies of the electron neutrino mass (up to now) are based on the investigation of the electron spectrum of tritium β decays:

$$\boxed{{}^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_e}$$

  - Energy spectrum of a neutrino with mass m_ν is given by:

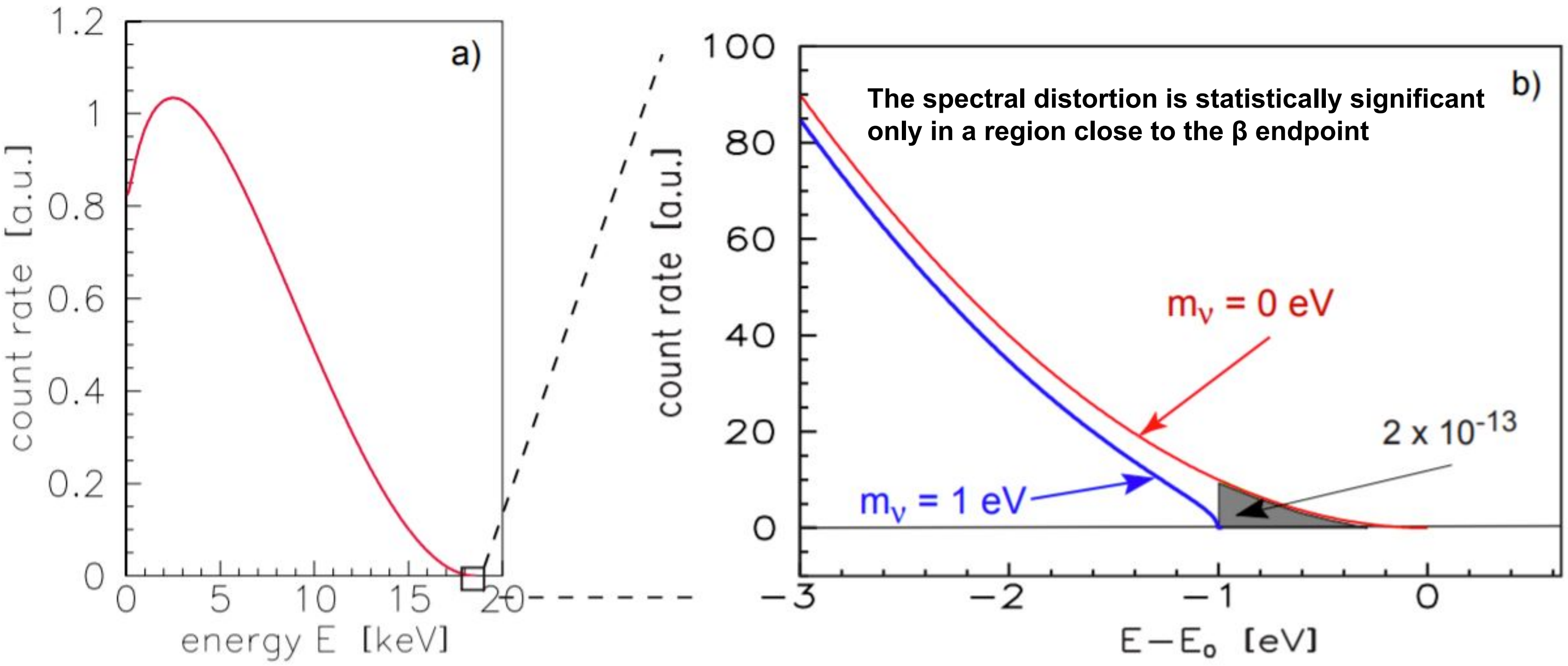
$$\frac{dN}{dE} \sim (E_0 - E)$$

kinetic energy of the electron

endpoint energy (i.e. maximal electron energy for m_ν=0)

  - Neutrino mass leads to a “distortion” of the energy spectrum of the neutrino
  - independent of whether the electron neutrino is a Majorana or a Dirac particle.

Neutrino mass measurements



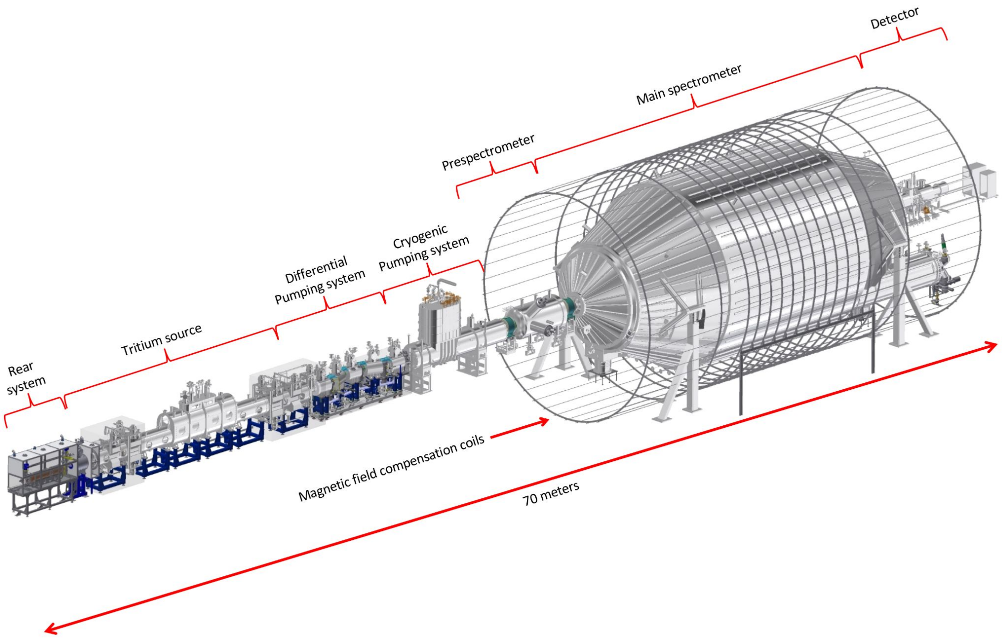
The electron energy spectrum of tritium β decays for (a) the complete and (b) the narrow region around the endpoint energy E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

Taken from: https://www.katrin.kit.edu/publikationen/DesignReport2004-12Jan2005.pdf

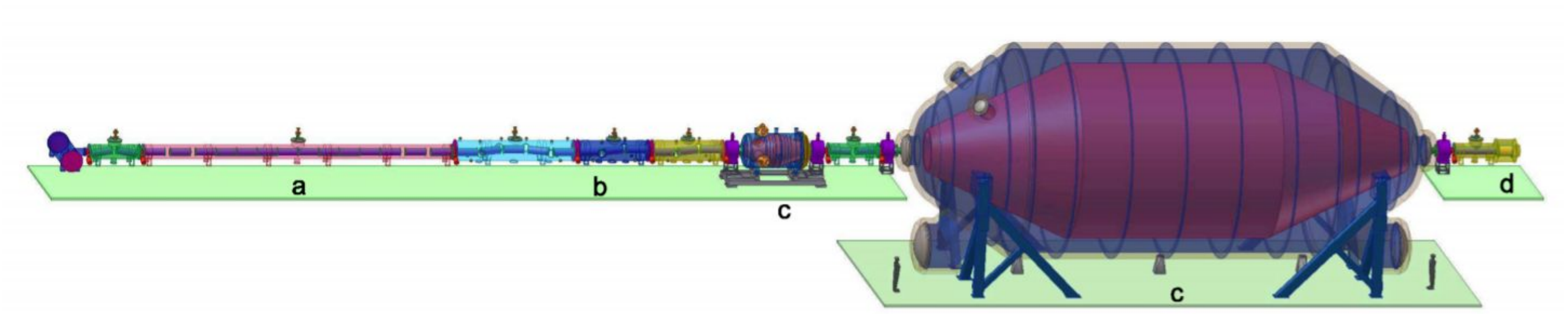
KATRIN

- **Karlsruhe Tritium Neutrino** Experiment (**KATRIN**) aims to directly measure the mass of the electron neutrino
  - Taking data since 11. Juni 2018

- **Why use tritium ?**
  - Tritium has a particular low endpoint energy of E_0 = 18.6 keV
  - Tritium has a rather short half life $t_{1/2}$ = 12.3 a
  - Simple electron shell configuration (i.e. simple correction terms due to interaction of β-electrons with the tritium source)
  - inelastic scattering of out-going β-electrons within the β source are small.



KATRIN

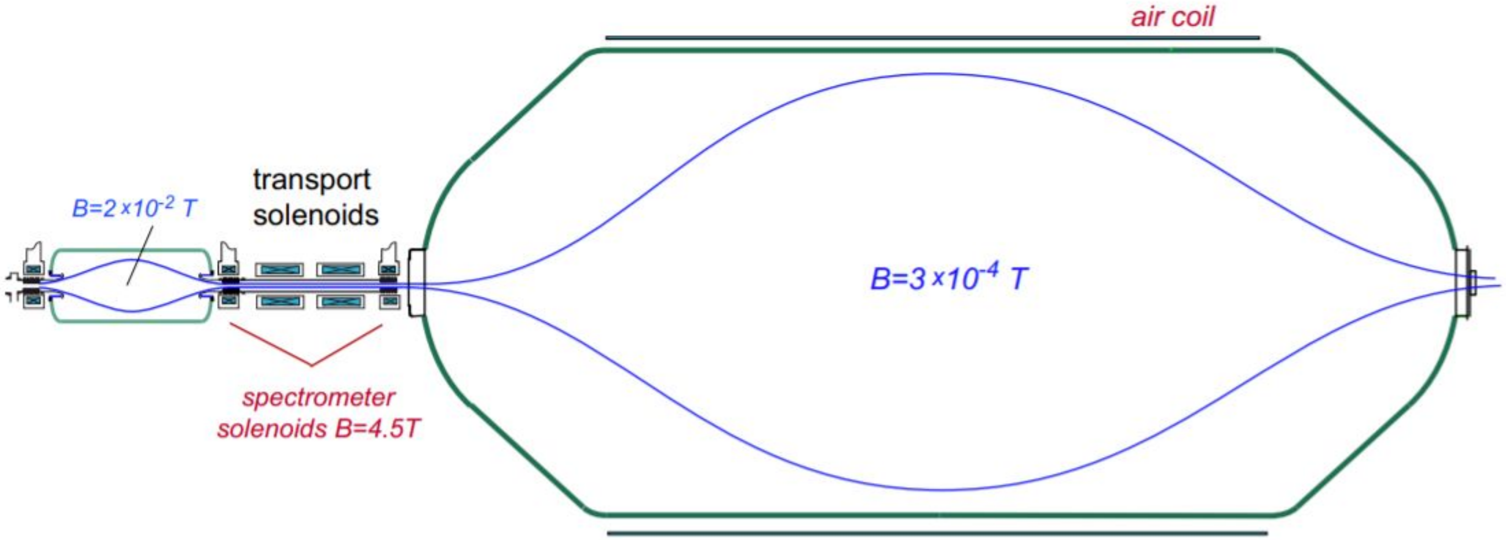


The 70 m long KATRIN reference setup with its major components:

- a) the gaseous tritium source
- b) the transport elements (i.e. an active pumping part and a passive cryotrapping section)
- c) the two electrostatic spectrometers
- d) the detector for β-counting

Taken from: https://www.katrin.kit.edu/publikationen/DesignReport2004-12Jan2005.pdf

KATRIN



- The two electrostatic spectrometers of KATRIN act basically as filter:
    - Electrons with less energy than a retarding potential are reflected
        - **Only want to analyse electrons with energies close to E_0**

Taken from: https://www.katrin.kit.edu/publikationen/DesignReport2004-12Jan2005.pdf